INTERNATIONAL FIELD YEAR FOR THE GREAT LAKES

GL BULLETIN (SPECIAL) NO. 20

PRECIPITATION (RADAR) PROJECT of the IFYGL LAKE METEOROLOGY PROGRAM

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J. W. Wilson
D. M. Pollock

UNITED STATES

DEPARTMENT OF COMMERCE

DEPARTMENT OF DEFENSE

DEPARTMENT OF INTERIOR

DEPARTMENT OF TRANSPORTATION

ENVIRONMENTAL PROTECTION AGENCY

NATIONAL SCIENCE FOUNDATION

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ONTARIO MINISTRY OF NATURAL RESOURCES

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LAKE METEOROLOGY PROGRAM

PRECIPITATION (RADAR) PROJECT

by

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The Center for the Environment and Man, Inc.
Hartford, Connecticut
(under contract number NOAA 03-5-022-17,
National Oceanic and Atmospheric Administration)

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Downsview, Ontario

June 1977

PREFACE

It has been the stated intention of the IFYGL Steering Committee and the Joint Management Team to bring together a final overview in depth of the IFYGL programs in what was originally termed the IFYGL Final Scientific Report Series. For this purpose the following titles and authorships were established:

The Terrestrial Water Balance of Lake Ontario and Its Basin
- B.G. DeCooke and D.F. Witherspoon

The Energy Balance of Lake Ontario
- A.P. Pinsak and G.K. Rodgers

The Water Movement Program
- E.B. Bennett and J.H. Saylor

The Lake Meteorology Program

(a) Atmospheric Water Balance Project
- E.M. Rasmusson and H.L. Ferguson

(b) Precipitation (Radar) Project
- J. Wilson and D.M. Pollock

(c) Basin-Wide Meteorological Analyses
- D.W. Phillips and J.A. Almazan

The Atmospheric Boundary Layer Program
- J.Z. Holland and F.C. Elder

The Biology and Chemistry Programs

(a) Status of the Biota of Lake Ontario
- N. Thomas and W.J. Christie

(b) Materials Balance of Lake Ontario
- D.J. Casey, A. Fraser and K. Crawford

(c) Results of IFYGL Chemical and Biological Research
- W.J. Christie and N. Thomas

Evaporation Synthesis Program
- F.H. Quinn and G. den Hartog

IFYGL Summary Volume
- T.L. Richards and E.J. Aubert

It is now the intent of the Joint Management Team to publish the entire series in one,or possibly two, hard covered volumes under the title, "IFYGL - A Scientific Summary of the International Field Year for the Great

Lakes." Each section will undergo scientific and editorial reviews with the final editorial responsibilities belonging to the Scientific Editors.

The section on "Precipitation (Radar) Project" was the first to complete the review and editorial processes. As it will be some time before the final publication goes to press it was agreed to make this report available as a Special Edition of the IFYGL Bulletin. In this connection, acknowledgements are due to the:

Scientific Reviewers	- anonymous senior scientists
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ABSTRACT

Precipitation measurements for Lake Ontario and its watershed were derived for the 1-year period from April 1972 to March 1973 of the International Field Year for the Great Lakes (IFYGL). Eight techniques were used in obtaining the estimates. Seven of the techniques were based solely on precipitation gage data. The eighth combined data from two weather radars and 167 precipitation stations to produce a detailed precipitation analysis for the entire basin for each day of the Field Year. The precipitation observation systems and measurement techniques are described, and measurements are compared.

Accuracies of the precipitation estimates are evaluated based largely on withheld data from three mesonetworks of rain gages. The average error in the monthly precipitation amounts for the watershed is less than 5 percent and between 10 and 15 percent for overlake estimates. In addition, it is estimated the measurements for the warm season average another 7 percent too low. Confidence in the precipitation estimates and accuracy figures for the cold season are relatively low because of difficulties in accurately measuring snowfall.

The lake had a discernable effect on the precipitation approximately one-half of the precipitation days. During the warm season, this was by suppressing shower activity over the lake and during the cold season by initiating shower activity over and downwind of the lake. The days on which the lake had the greatest impact on precipitation patterns were characterized by scattered, light showers. Thus, while the lake frequently influences precipitation patterns, its effect on total season precipitation is less apparent.

1. INTRODUCTION

Four separate projects associated with the International Field Year for the Great Lakes (IFYGL) in 1972-73 had as their objective the measurement of precipitation falling on Lake Ontario and/or on the land within the Ontario basin, shown in figure 1, to meet requirements by both the Lake

Figure 1. -- Topography of Lake Ontario basin, showing elevation in meters.

Meteorology and Terrestrial Water Balance Programs of IFYGL. The original objectives of the precipitation projects are contained in the IFYGL Technical Plan, Vol. I (1972). Primary objectives were to:

a) Measure the daily total precipitation falling on the lake and land portion of the Lake Ontario basin.

b) Estimate the accuracy of the precipitation measurements.

c) Determine the type of precipitation falling on the lake.

d) Investigate land-to-lake precipitation differences.

Precipitation data were available from three weather radars and 376 precipitation gages. Most of the gages used were the Canadian and United

States first order and climatological stations. Gage data were also obtained from special island, shoreline, and tower installations. For snow measurement studies and error analyses, three precipitation gage mesonetworks were installed.

This report summarizes the results of the following four projects, highlighting major findings:

(1) Basin Precipitation-Land and Lake - a cooperative effort by D.M. Pollock of the Canada Atmospheric Environment Service (AES) and J.W. Wilson of The Center for the Environment and Man, Inc.

(2) Island-Land Precipitation Analysis, by D.C. Norton and S.J. Bolsenga of the Great Lakes Environmental Research Laboratory, NOAA.

(3) Canadian Land Precipitation, by J.G. Irbe of Canada AES.

(4) Land-Lake Precipitation Data Analysis, by B.G. DeCooke of the U.S. Army Corps of Engineers and D.F. Witherspoon of the Canada Department of the Environment.

The first project (Basin Precipitation-Land and Lake) was the biggest of the four. It provided daily precipitation measurements for the entire lake and land portions of the Ontario basin on a grid with a resolution of 6.5 km. These were the only measurements made on a sufficiently small scale to enable an error analysis to be made over the gage mesonetworks. Also, it was the only project in which both radar and gage data were used, and the results of this project therefore constitute a major part of this report. The other three projects provided either daily or monthly average precipitation totals for the lake, the United States watershed, or the Canadian watershed. These three projects based their measurements entirely on gage reports, with the Thiessen polygon procedure generally used for determining the area weighting factor for each gage. The data and analysis procedures used in each project are summarized in section 3.

Monthly precipitation totals as derived by eight different techniques are presented in section 4.1. Daily precipitation totals and information on type of precipitation are not presented in this report, but are given by Wilson (1975a). Differences between land and lake precipitation are discussed in section 4.4, and the accuracy of the precipitation measurements is evaluated in section 5. Section 6 contains recommendations for future projects of this type.

This summary report is based partly on reports by Bolsenga and Hagman (1975), DeCooke and Witherspoon (1974), Hansen et al. (1973), Norton (1975), Peck et al. (1974), Wilson and Pollock (1974), and Wilson (1975a, 1975b, 1976, and 1977), to which readers are referred for specific details not provided in this report.

2. DESCRIPTION AND PERFORMANCE OF OBSERVATION SYSTEMS

Three weather radars (2 United States, 1 Canadian) and 376 precipitation gages (138 United States, 238 Canadian) were available for measuring precipitation over Lake Ontario and its watershed during IFYGL. Radar data were acquired from three locations: the National Weather Service WSR-57 at Buffalo, New York; a Vitro MR-782 at Oswego, New York; and a Curtis Wright FPS-1001 at Woodbridge, Ontario. Three precipitation gage mesonetworks were operated during portions of the Field Year. They were located near Rochester, N.Y., Oswego, N.Y., and Bowmanville, Ontario, and were used primarily for error analysis. The locations of the gages, radars, and mesonetworks are shown in figure 2. A full description of the United States data acquisition system is contained in IFYGL Technical Manual Series No. 4 (Hansen et al., 1973); details of the Canadian acquisition system are given in the appendix of this report.

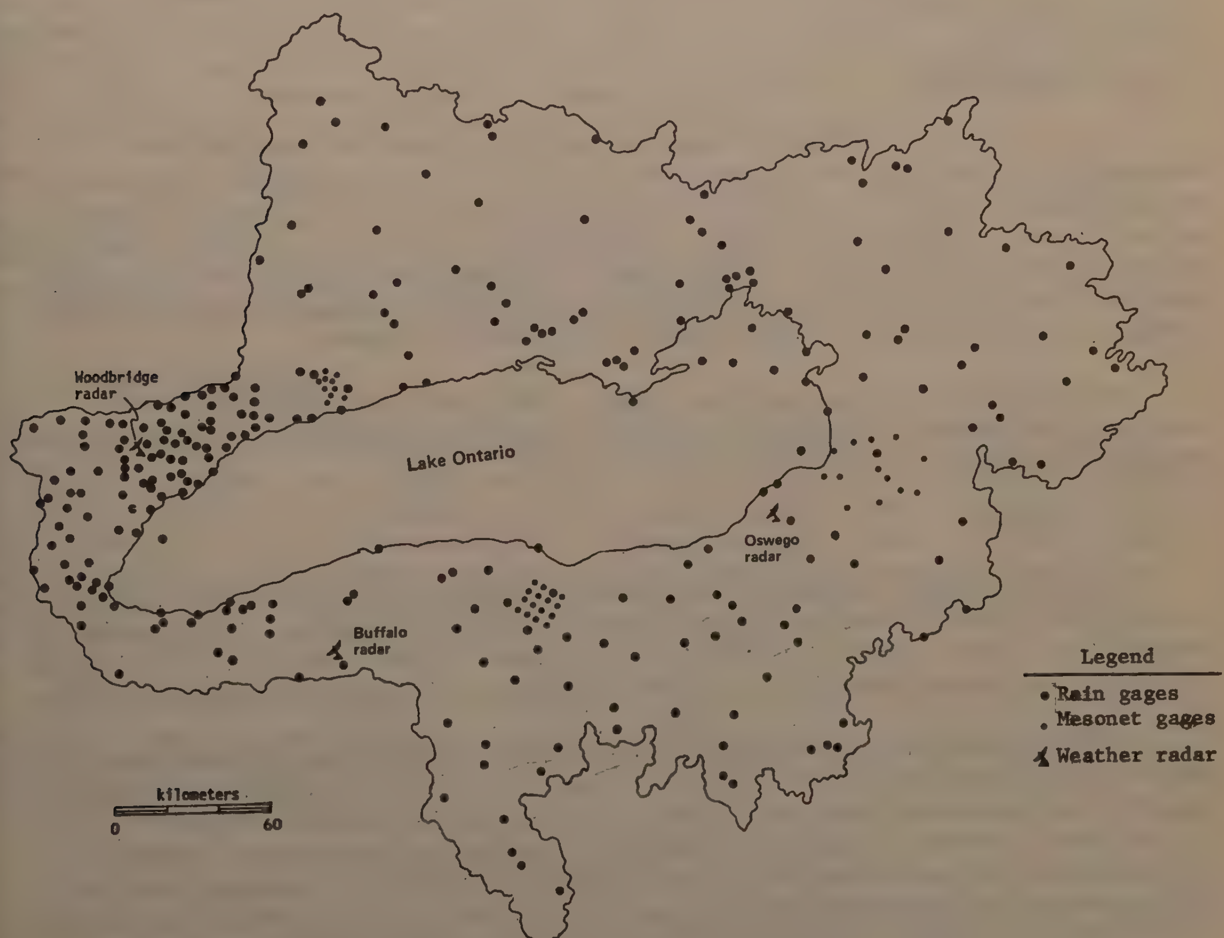

Figure 2.--Location of rain gages and weather radars used for IFYGL data collection.

2.1 Gage Mesonetworks

2.1.1 Rochester

The Rochester Rain Gage Network contained 16 recording gages of the Fischer and Porter type in a 170 km^2 area south of Rochester, N.Y., and was operational during the entire Field Year. The gages had a depth resolution of 0.1 in.* and a time resolution of 15 min. The exposure to wind varied between sites, and the gages had no wind shields. Since no special effort was made to protect the gages from wind, they suffered large undercatch in snow. This combined with the 0.1-in. resolution made the gages unreliable for winter use.

During rain there was evidence that some gages underestimated by as much as 5 to 10 percent relative to another. Because of the 0.1-in. resolution, the network was used only for storms where the rainfall exceeded this value.

2.1.2 Bowmanville

A network of 12 tipping bucket-type rain gages was located near Bowmanville, Ontario, in an area of 85 km^2. It was operated from April 1972 to November 15, 1972. Data were recorded on weekly strip charts, from which it was possible to obtain a resolution of 0.01 in. in depth and 1 hr in time. The Bowmanville network gages systematically measured 10 to 15 percent less rain than the surrounding climatological gages, apparently because of an error in calibration of the network gages.

A distrometer (Joss and Waldvogel, 1967) was located within the network, and measured the number and size of the raindrops during the April-November period.

2.1.3 Oswego

The Oswego snow network contained 13 weighing recording-type gages in an area of 850 km^2, and was operational from late November 1972 through March 1973. Data were recorded on strip charts, each pen traverse across the chart representing 24 hr. Depth resolution to 0.01 in. was possible.

This network was established specifically for accurate snow measurements. Each gage site was carefully chosen to provide maximum natural protection possible from wind, and six gages had Alter wind shields. The gages were generally located in small clearings in coniferous forests where trees subtented angles of approximately 45° from the gage orifice. The network has been described in detail by Peck et al. (1973), who conclude that the catch of these gages is close to the "true" snowfall.

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*Throughout this report precipitation is reported in inches since that was the unit used during the measurements. All other units are metric.

Eighty high-school students living within the gage network made measurements of snow at least once a day. They measured snow depths and water content, the latter by taking cores to a snow board and then melting the snow. Snow crystal types and sizes were observed visually by exposing a black felt board to the falling snow. The observers also obtained replicas of snowflakes, and six students were equipped with cameras for closeup photography of flakes.

The data from the Oswego network were essential in developing radar techniques for measuring snowfall.

2.2 Climatological Networks

2.2.1 Canada

Approximately 240 Canadian climatological network stations are located within the Ontario watershed. Most of the rainfall is measured with nonrecording gages, which are read to the nearest 0.01 in. between 7 and 9 a.m. daily. Approximately 60 recording gages of the tipping bucket and Fischer and Porter type are included within this network.

The primary instrument for measuring snowfall is a ruler, which is used to measure the depth of freshly fallen snow to the nearest 0.1 in. The depth is converted to water content by assuming a density of 0.1. Approximately 10 Nipher snow gages are also part of the network. A detailed description of the different gage types is given in the appendix.

2.2.2 United States

Approximately 93 standard United States climatological network gages are located within the Ontario watershed. Fifteen are recording type gages, 12 have a 0.01-in. resolution, and 3 are Fischer and Porter gages with a resolution of 0.1 in. The remaining 78 gages are read once a day by volunteer observers. These gages are read at a variety of times; however, the majority are read between 7 and 9 a.m. These gages are copper cylinders, 20 cm in diameter, mounted 79 cm above the ground.

Water equivalent values for snowfall are obtained in a variety of ways: the most common by melting the snow that falls into the gage; by melting core samples from fallen snow; and by using a ruler and a snow depth-to-water equivalent ratio of 10 to 1.

2.3 Other Precipitation Networks

Six other IFYGL data acquisition programs included precipitation gages that collected data during the Field Year. However, for various reasons these data were not used, or only to a limited extent. Three systems installed specifically for IFYGL were the Bedford towers, the Canadian shoreline network, and the United States shoreline network (frequently referred to as the Physical Data Collection System). Processing of the data from the first two had not been completed when this study was undertaken.

The data from the United States shoreline network were not used because of the high rate of missing and erroneous observations caused by instrument malfunctions.

A network of Fischer and Porter type gages was operated along the northeastern shoreline of the lake. Because of their exposed locations, which resulted in substantial undercatch during snowfall, and because many measurements were missing, these data were used only sparingly for this study.

Two other precipitation gage mesonetworks were being operated in Canada during IFYGL for other research purposes. The first is the Uxbridge network, consisting of nine tipping bucket recording gages located between 43°57' and 44°5'N latitude and 79°3' and 79°16'W longitude. The second is a network of 19 tipping bucket recording gages located in the vicinity of Toronto for forecast research. The data from these networks were not used in preparing the precipitation estimates given in this report, but the location of the gages will make the data useful for assessing the accuracy of rainfall estimates from the Woodbridge radar when they become available.

2.4 Weather Radars

2.4.1 Woodbridge

The Atmospheric Environment Service FPS 1001 radar at 43°43'N, 79°33'W, northwest of Toronto, is normally operated for research purposes and only at times of significant precipitation. During the Field Year, April 1 1972, to March 31, 1973, the radar was operated continually whenever precipitation was occurring, or was expected to occur, within range of the radar. The data were recorded on 35-mm film in CAPPI format. The CAPPI recording operation is summarized below. Film is available for 27.2 percent of the year. No significant breaks in the record were caused by radar malfunction.

Summary of CAPPI Recording Operation

Period:	4/1/72-2/20/73	2/20/73-3/31/73
Measurement cycle:	15 min	6 min
Altitude:	1524 m (5000 ft) 3657 m (12,000 ft) 5791 m (19,000 ft) 7925 m (26,000 ft)	1500 m 3000 m 5000 m 7000 m

The Woodbridge radar has a wavelength of 5 cm and a beam width of 1.1°. The antenna was mounted on a tower and centered at 22 m above ground to give an unobstructed view in all directions. The data were recovered from the film using a flying spot scanner that positions a 256 x 256 raster over the

185-km range radar display (Pollock, 1972). The transmittance of the film was measured with a resolution of 1 part in 64 for each element in the raster (1.5 x 1.5 km). These data were fed to a computer and converted to values of the power returned to the radar by comparison with a set of calibration bars on the film. The Woodbridge radar data were not used for this report because they are still being processed.

2.4.2 Buffalo

The National Weather Service WSR-57 radar at Buffalo, N.Y., at 42°56'N, 78°44'W, was used for measuring precipitation over the western portion of Lake Ontario and its watershed. The radar has a wavelength of 10 cm and a beam width of 2°. For IFYGL, a digitizer, processor, and magnetic tape recorder were added to the radar. The radar-received power was averaged for an area 1.85 km in range by 2° in azimuth. The averaged signal was displayed on the radar scope in six quantized intensity levels and recorded on magnetic tape at 256 intensity levels. Data were collected for radar ranges from 20 to 231 km with the radar beam elevated at 0.5°. Additional details are given by Hansen et al. (1973).

It was intended to collect data on magnetic tape and 16-mm film whenever precipitation was within 222 km of the radar. A complete radar scan was to be recorded on 16-mm film every 5 min and on magnetic tape every 10 min. Useful data were recorded on tape 68 percent of the hours that precipitation was falling over the basin. Missing observations were the result of hardware malfunctions and operator error. Many of the missed collections resulted from the operator manually "overriding" the automatic collection feature of the radar system and then forgetting to return the system to automatic. Unfortunately, this occurred most frequently during significant precipitation periods. It was possible to use the PPI photographs to fill some of the gaps in the magnetic tape data.

2.4.3 Oswego

A Vitro Services Division Model MR-782 meteorological radar was installed especially for the IFYGL program. This radar was located 15 km south of Oswego, N.Y., at 43°19'N, 76°29'W. It was used for measuring precipitation over the eastern portion of Lake Ontario and its watershed. The radar had a wavelength of 5 cm and a beam width of 1.7°, and was equipped to average, digitize, and record on magnetic tape the returned signal. The radar-received power was averaged over an area 1.85 km in range by 2° in azimuth. The processed radar signal was displayed on a cathode ray tube showing six intensity levels and recorded on tape for 16 levels. Data were collected with the radar beam elevated at 0.9° for radar ranges from 15 to 222 km. Additional details are contained in the report by Hansen et al. (1973).

Data were successfully collected on tape for 82 percent of the hours that precipitation occurred over the basin within the range of the radar. Essentially, all the missing and bad data occurred during two extended

time periods of 41 and 27 days. Both missing data periods were associated with hardware malfunctions. Operator errors were few compared with those that occurred at Buffalo, because the operators at Oswego were hired for the sole purpose of collecting data for IFYGL. At Buffalo, the IFYGL observations were added to the operators' existing duties. If a 2-to-3-month "shakedown" period before the start of the Field Year had been possible, the data from both radars would have been greatly improved.

Because the radar beam was blocked by trees near the Oswego radar site, data had to be discarded for three sectors, which subtended angles of 8, 26, and 54°. Fortunately, none of these sectors was over the lake.

3. ANALYSIS METHODS

Basin and lake precipitation values were derived by eight different methods, seven of which were based on gage data. One was based on both radar and gage data. In what follows, each technique is identified by the name of the investigator who supplied the precipitation measurements.

3.1 Irbe - Canadian Watershed

The Atmospheric Environment Service (AES) has been issuing a monthly bulletin of average precipitation on the Canadian portions of the land basins of the Great Lakes and Ottawa River since the early 1960's. J.G. Irbe, AES, derived estimates of precipitation amounts for the Lake Ontario land basin during IFYGL by the established routine method, i.e., by applying the Thiessen polygon technique to data from a subset of the first-order and climatological stations operating in or near the basin. In the selection of the data subset, two criteria were used: reasonably balanced spatial distribution of stations, and quality of station data. Figure 3a shows the locations of the gages chosen.

The monthly total precipitation amounts at each station were multiplied by the appropriate areal weighting factor and the products summed to arrive at the average monthly precipitation over the land basin. Because the Thiessen polygon method is too cumbersome and time-consuming to justify recalculation of station weighting factors for every month, the monthly precipitation amounts at stations for which data were missing were estimated from nearby observations. During IFYGL approximately 7 percent of the monthly precipitation values had to be estimated. If a station was officially closed or was consistently late in sending in reports, it was removed from the subset and a substitute inserted.

3.2 Norton - U.S. Watershed

Daily precipitation measurements for the United States land portion of the Lake Ontario basin were derived by Norton (1975). The daily values were based on 57 National Weather Service climatological stations within the Ontario basin. Their locations are shown in figure 3b. These stations include only those whose 24-hr measurements were taken between 7 a.m. and 10 a.m.

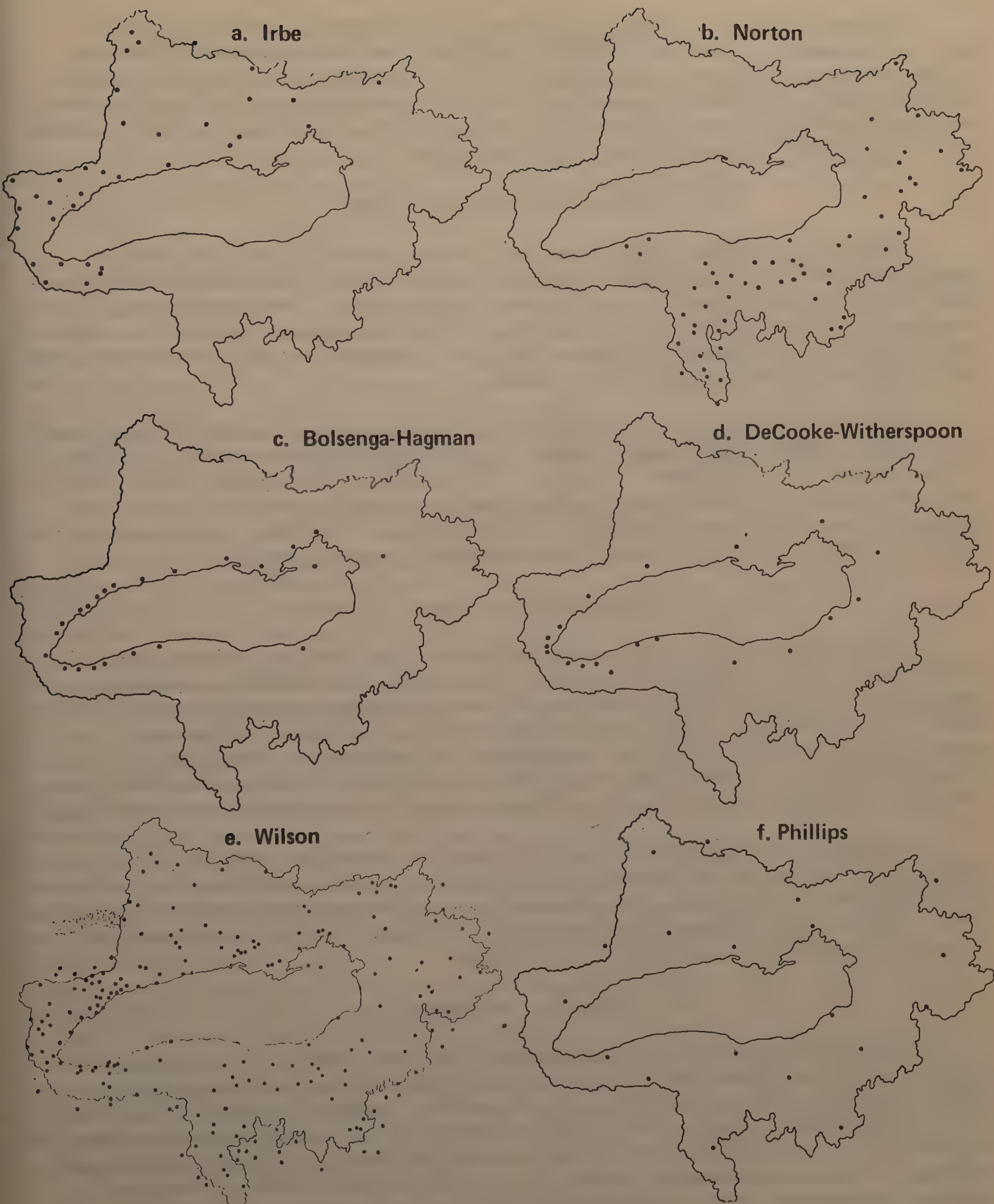

Figure 3.--Precipitation stations used by each investigator.

The areal weight assigned each gage was determined by the Thiessen polygon procedure. The daily totals were derived by summing the products of the daily gage amounts and weights. The procedure for handling missing stations was equivalent to assuming that the precipitation falling in the polygons for which data were missing was equal to the average precipitation of the polygons for which data were available.

3.3 Bolsenga and Hagman - Lake

Bolsenga and Hagman (1975) derived average monthly precipitation totals for Lake Ontario based on monthly gage amounts from 22 shoreline gages and one gage located on an island in the lake. The gages were selected from the United States and Canadian climatological networks. The gage locations are shown in figure 3c. The Thiessen polygon method was used to determine the weight given each gage.

Because of the sparse distribution of gages on the United States side, three gages (Main Duck Island, Wolcott, and Barker) account for 42 percent of the weights. An attempt was made to fill these data-sparse areas with data from gages at some distance from the lake, but this resulted in consistently too high lake estimates for May through September and consistently too low estimates for the period from October through April.

3.4 DeCooke and Witherspoon - Lake

Average monthly precipitation totals were derived by DeCooke and Witherspoon (1974) for Lake Ontario. The totals were based on monthly measurements from 20 United States and Canadian gages located around the lake. The location of the gages is shown in figure 3d. The average precipitation for the lake was determined by summing the means of the observations on the north and south sides, and then dividing the sum by two. The north side mean was based on 12 gages and the south side mean on 8 gages.

The gages were generally farther from the shoreline than those selected by Bolsenga and Hagman. Each gage was given equal weight, but a larger number of the gages were located along the west and southwest shoreline, and the lake average is therefore disproportionately dependent on the precipitation that fell in those areas.

3.5 Pollock - Watershed

Using only precipitation measurements by stations in the standard United States and Canadian climatological networks (approximately 170), Phillips and McCulloch (1974) prepared monthly isohyetal analyses for the entire watershed. The locations of the gages were similar to those shown in figure 3e. D.M. Pollock, AES, planimetered the areas between isohyets and assigned these areas average depths of precipitation, and the overall average depths were then computed for the United States and Canadian land basins. The isohyetal analyses were not performed with this purpose in mind, and because the average depths between isohyets were assigned by the simplest method (average of the two isohyets) the results are not the best possible by the isohyetal method.

3.6 Phillips - Watershed

A major goal of this project was to compare total precipitation during IFYGL with normals computed from data for 1941 to 1970. A network of 20 stations, 10 on each side of the border, was selected (Phillips, 1974). Criteria used in choosing these stations were a lengthy record of good quality, and a balanced spatial distribution representative of various surface covers over the land portion of the basin.

The average precipitation for the land watershed was determined by summing the monthly totals, and then dividing the sum by 20. The arithmetic averaging method was tested against the Thiessen polygon and isohyetal techniques by a difference-of-means test based on data for several months prior to the Field Year. Weights assigned to each station by the Thiessen method averaged 0.05, with no station having an influence of more than 0.07 or less than 0.03. Because the results obtained by the three techniques showed no significant differences, the arithmetic averaging method was used for IFYGL. The locations of the stations are shown in figure 3f.

3.7 Wilson - Watershed and Lake

Daily precipitation amounts were determined for both the land and lake portion of the Lake Ontario basin. The daily values were derived for a 79 x 64 grid array covering the entire basin, with a separation between grid points of 6.5 km. Two estimates were obtained: the first, called "ANL2", was based on 167 United States and Canadian climatological and first-order precipitation gages; the second, or "FINAL", was based on the 167 precipitation gages and the Buffalo and Oswego weather radars. The locations of the gages are shown in figure 3e. The ANL2 estimates were obtained through a computer-produced objective analysis of data from the 167 rain gages. The technique for deriving the FINAL estimates consisted of four steps. First, the ANL2 precipitation field was obtained. Second, a radar adjustment field was determined from an objective analysis of the ratio between the individual gage estimate and the radar estimate for the gage site. Third, an adjusted radar precipitation field was obtained by multiplying the radar-derived precipitation field and the adjustment field. And fourth, a combined gage and adjusted radar precipitation field was prepared. The combined field was obtained by giving 100 percent weight to the gage field (ANL2) when a grid point coincided with a gage location, the weight given the gage field decreasing linearly to 0 percent and the corresponding weight to the adjusted radar field increasing to 100 percent as the distance from the nearest calibration gage increased to a prespecified distance. For areas without radar data, the gage analysis was used. In essence, the FINAL precipitation field was molded to fit the gage observations, while retaining variability between gages as observed by radar. Further details of the technique are given by Wilson (1975a).

4. RESULTS

4.1 Comparison of Techniques

The precipitation estimates obtained by the eight techniques described in section 3 are compared in this section. Since these estimates are not all for the same area and time period, the number of comparisons that can be made is limited. The ANL2 and FINAL estimates are the only ones that include the entire land and lake basin and any area within it. The others are single-area averages. Table 1 lists the names of each investigator who supplied precipitation estimates and the area and time interval covered.

Table 1.--IFYGL precipitation measurements

Investigator	Area of measurement	Time period	Data source	Density (km^2/gage)
Irbe	Canada	Month	33 gages	950
Norton	United States	Day	57 gages	686
Bolsenga-Hagman	Lake	Month	23 gages	837
DeCooke-Witherspoon	Lake	Month	20 gages	961
Pollock	Canada; United States	Month	170 gages	411
Phillips	Canada; United States	Month	20 gages	3522
Wilson (ANL2)	Canada; United States	Day	167 gages	536
Wilson (FINAL)	Canada; United States	Day	167 radar & gages	536

In tables 2, 3, and 4 the estimates by the various investigators are compared with the FINAL estimates. Results are given for monthly and yearly totals available for the United States watershed, the Canadian watershed, and Lake Ontario. Table 5 presents statistics comparing each technique with the FINAL measurements. As seen in this table, the monthly totals for all techniques are highly correlated. The FINAL yearly totals average 1 to 6 percent more than the other estimates, the differences being greatest for the overlake measurements. This was expected since the overland FINAL estimates are heavily dependent on the same gage data as those used in the other techniques, while the overwater FINAL estimates are heavily dependent on radar data.

Table 2.--FINAL monthly precipitation estimates for Lake Ontario compared with ANL2, Bolsenga, and DeCooke results based on Canadian precipitation day*

Month	FINAL precipitation totals (in.)	Difference (%)		
		ANL2	Bolsenga	DeCooke
Apr. 1972	2.56	0	3.9	5.8
May "	3.32	-0.3	2.1	-15.1
June "	4.56	-1.3	-5.9	3.7
July "	3.01	-7.6	-10.0	-8.6
Aug. "	3.62	1.6	0	21.0
Sept. "	2.76	9.1	4.7	8.3
Oct. "	3.37	-5.6	-3.9	7.4
Nov. "	4.68	-12.8	-7.5	-22.6
Dec. "	4.27	4.4	8.2	-5.8
Jan. 1973	2.21	-26.2+	-27.6+	-22.2+
Feb. "	2.19	-8.2	-7.3	-5.4
Mar. "	4.34	-3.2	-2.3	2.8
TOTAL	40.89	-3.7	-3.1	-2.7

* The United States commonly defines the precipitation falling during the 24-hr period ending at 1200 GMT as the precipitation for the day at the end of the measurement period. Canada generally defines it as the precipitation for the day the precipitation measurement period begins.

+ These large differences are attributed to localized "lake effect" snowstorms occurring primarily over the lake and the "snowbelt" east of the lake; shoreline gages simply did not adequately sample these storms.

Table 3.--FINAL monthly precipitation measurements for U.S. watershed, based on the appropriate precipitation day, compared with ANL2, Norton, Pollock, and Phillips measurements

Month	FINAL precipitation totals (in.)		Difference (%)			
			ANL2	Norton	Pollock	Phillips
	Canada	U.S.	Canada	Canada	U.S.	U.S.
Apr. 1972	2.64	2.64	0	-4.1	6.4	8.0
May "	5.14	4.48	-1.6	-2.0	1.1	1.6
June "	8.12	8.56	-0.8	-0.2	4.8	0
July "	3.91	4.13	-2.8	-0.5	-13.1	-8.7
Aug. "	3.54	3.55	-6.2	3.0	-0.8	5.4
Sept. "	3.26	3.00	-1.0	-4.6	7.0	9.0
Oct. "	3.25	3.51	-1.7	-2.5	-7.4	-5.4
Nov. "	5.47	5.14	-2.0	-2.9	4.5	8.6
Dec. "	4.49	4.42	-3.1	-4.9	-3.8	-2.9
Jan. 1973	2.11	2.51	-6.7	-2.0	-12.0	-10.4
Feb. "	2.28	2.28	-3.4	-2.6	-6.1	0
Mar. "	3.39	3.17	-1.6	-3.5	-7.3	-8.8
TOTAL	47.61	47.39	-2.3	-2.0	-1.3	0

Table 4.--FINAL monthly precipitation measurements for Canadian watershed compared with ANL2, Irbe, Pollock, and Phillips measurements based on Canadian precipitation day

Month	FINAL precipitation totals (in.)	Difference (%)			
		ANL2	Irbe	Pollock	Phillips
Apr. 1972	1.99	0	2.9	0	1.5
May "	3.29	-0.8	-5.2	-5.5	-7.3
June "	4.44	-1.3	-3.6	-4.1	-5.9
July "	2.95	-2.7	-14.6	1.7	-20.3*
Aug. "	3.73	-2.6	-5.3	0.3	-12.1
Sept. "	2.99	-1.4	-4.3	-3.3	-0.7
Oct. "	3.56	-0.7	-0.7	0.3	0.6
Nov. "	3.40	-1.4	-5.6	-8.2	-9.4
Dec. "	5.30	-0.1	-6.5	-6.8	-9.4
Jan. 1973	1.90	-2.1	-3.2	4.7	-2.1
Feb. "	1.84	-1.2	-5.9	4.3	-1.6
Mar. "	4.06	0	-2.0	2.0	-0.5
TOTAL	39.45	-1.1	-3.8	-2.0	-6.2

* This difference was due to heavy rainfalls that were not measured by the particular gages selected by Phillips; approximately 15 percent of the area had more than 4 in. of rain, but none was recorded by Phillips' gages.

Table 5.--Comparison of measurements by each technique for each area with FINAL measurements

Area	Technique ANL2	Bolsenga	DeCooke	Norton	Irbe	Pollock	Phillips
(a) Coefficient of correlation (month totals)							
Lake	0.99	0.96	0.88	-	-	-	-
U.S.	0.99	-	-	0.99	-	0.99	0.99
Canada	0.99	-	-	-	0.99	0.99	0.98
(b) Year totals difference (%)							
Lake	-3.7	-3.1	-2.7	-	-	-	-
U.S.	-2.3	-	-	-2.0	-	-1.3	0
Canada	-1.1	-	-	-	-3.8	-2.0	-6.2
(c) Monthly totals average absolute difference (%)							
Lake	6.7	7.0	10.4	-	-	-	-
U.S.	2.6	-	-	2.7	-	6.2	5.7
Canada	1.2	-	-	-	4.9	3.4	6.0

(a) FINAL vs. technique

(b) [(FINAL - technique)/FINAL] x 100

(c) (|FINAL - technique|/FINAL) x 100

The high correlation between techniques, particularly for the overland estimates, is directly attributable to the large area and long time period involved. For areal averages over such large areas and long time intervals relatively few gages are required to adequately sample the precipitation. In all except Phillips' technique, gage densities of 410 to 950 km^2 per gage were used. This variation in data density had no obvious impact on the accuracy of the monthly results. Phillips used only 20 gages for 70,400 km^2 or 3520 km^2 per gage, which may be the cause of the relatively large differences shown in table 5.

The ANL2, Bolsenga, and DeCooke overlake rainfall measurements given in table 2 for May through October 1972 are within 2.5 percent of the FINAL measurements. This is better than might be expected since the FINAL estimated average precipitation along the immediate shoreline is 4.9 percent greater than the FINAL estimate over the lake. However, in the ANL2 and Bolsenga measurements the Main Duck Island gage in the northeastern part of Lake Ontario was used to estimate the precipitation for much of the eastern quarter of the lake. Use of shoreline gages in this area would have caused large overestimates. Also, the few gages used by Bolsenga to estimate precipitation for the eastern two-thirds of the lake happen to be located in regions of minimum rainfall. DeCooke's estimates were 2.5 percent higher than the FINAL estimates. One would expect them to be even higher since several of the gages are located inland in areas of heavier rainfall, but this was counterbalanced by the averaging procedure, which gives more weight to the gages at the western end of the lake where the precipitation was less. The western half of the lake received 17 percent less rain than the eastern half.

For the cold season, the Bolsenga, DeCooke, and ANL2 estimates average 5 to 10 percent less than the FINAL. It is also expected that the FINAL measurements themselves are 7 percent less than the actual (Wilson, 1975). Estimates for the cold season are particularly uncertain because of gage undercatch during snowfall. The only certainty is that the overlake estimates are less than the actual precipitation. Before reliable cold season precipitation measurements can be made, great care must be taken to locate gages in areas well protected from wind.

Daily precipitation estimates for the United States watershed were provided by Norton. When compared with the FINAL daily estimates, the coefficient of correlation is still 0.99, but the average daily difference is 31 percent compared with 3 percent for the monthly average difference. The average daily difference between the ANL2 and FINAL estimates ranges from 8 percent for the Canadian watershed to 38 percent over the lake. Characteristically, as the time period of measurement decreases, the error in the gage estimates of the areal average increases.

The spatial differences between the ANL2 and FINAL measurements for May through October 1972 and November 1972 through March 1973 are illustrated in figure 4. The characteristic of the FINAL technique to mold the precipitation field to the gage measurements is quite apparent. Almost all significant differences between the two techniques are seen in areas

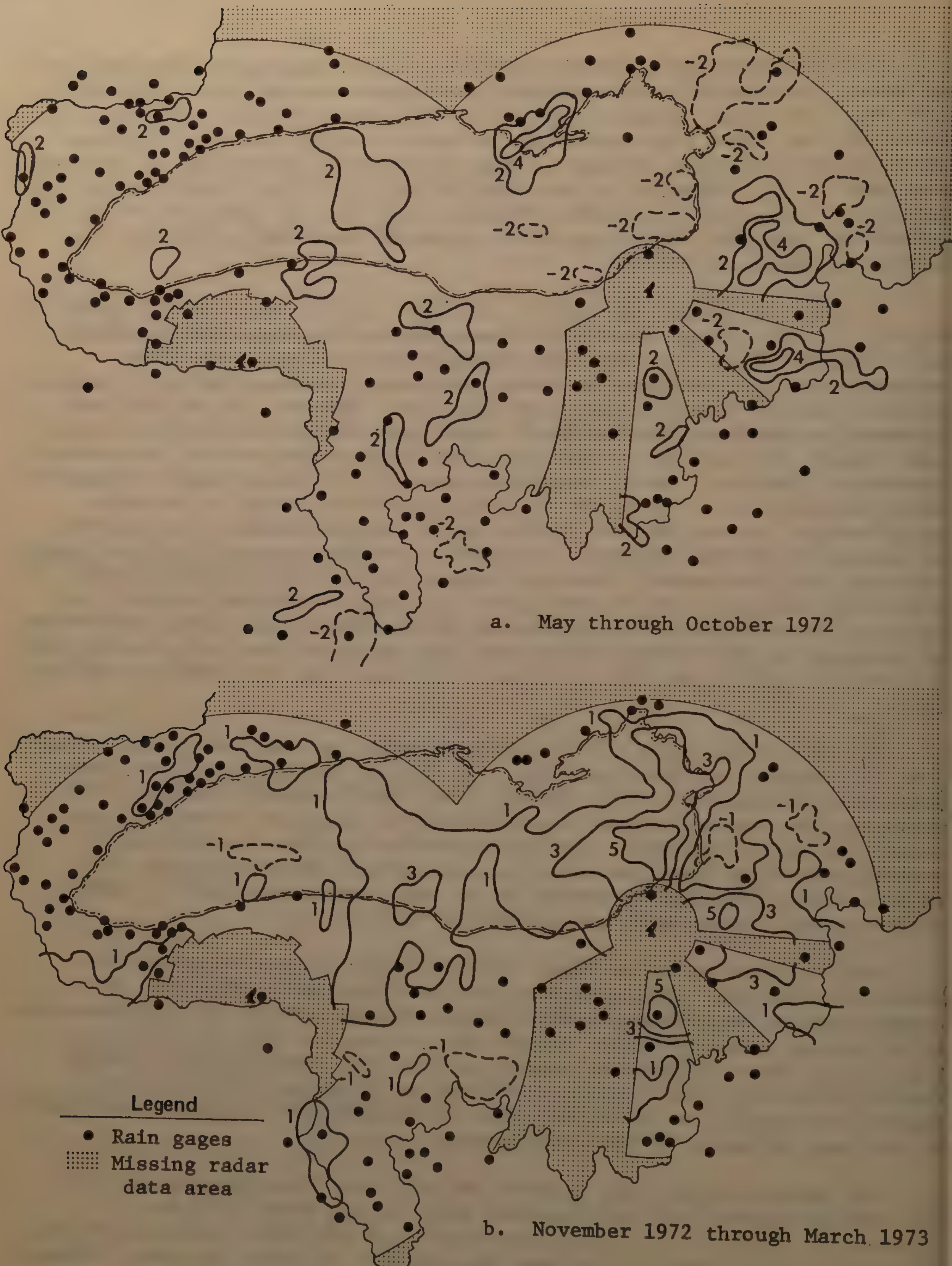

Figure 4.--FINAL minus ANL 2 precipitation analysis (in.).

between gages. The primary difference is over the eastern two-thirds of the lake during the cold season, and is attributed to the absence of gages to detect "lake effect" snow bands. An area of major disagreement between techniques is over the Oswego network during both the warm and cold seasons, because this is a region of maximum precipitation and there is not a climatological rain gage in a location to adequately sample this maximum.

4.2 FINAL Measurements

FINAL precipitation totals for each day of the Field Year were produced for a grid covering the entire 93,200 km^2 of the Ontario basin. Each grid square was 6.5 km on a side. This data set was then analyzed by a computer to produce maps of precipitation distributions over the Ontario basin for various time periods. The grid-point totals were also averaged over designated areas, such as the gage mesonetworks, the lake, and the watersheds. Maps of precipitation distributions for the Field Year, May through October 1972, and November 1972 through March 1973 are shown in figures 5, 6, and 7, respectively. For maps of monthly basin precipitation totals, selected storms, as well as daily totals for the lake, the eastern part of the lake, the western part of the lake, the watershed, the United States watershed, and the Canadian watershed, the reader is referred to Wilson (1975a).

For the Field Year, the total precipitation over the watershed averaged 43.73 in.; over the lake, 40.39 in.* The total precipitation during the Field Year generally averaged 10 to 40 percent above normal, with a number of the stations reporting 1972 as the wettest year on record. The largest anomalies occurred in the southern portion of the watershed, which received very heavy rains from Hurricane Agnes. The distribution of the yearly precipitation was similar to the climatological distribution, with a maximum over the hills east and southeast of Lake Ontario. The precipitation maximum in the extreme southern watershed was atypical, and was a direct result of Hurricane Agnes.

Figure 6 indicates that the overlake precipitation was generally less than that over land during the warm season from May through October. Conversely, figure 7 shows a tendency during the cold season for a precipitation maximum over the lake extending downwind of Lakes Ontario and Erie. The precipitation distribution in figure 7 is different in two respects from the actual map derived from the FINAL totals. The map was revised to correspond more closely to the radar data, because it was believed that large "undercatch" byseveral gages during snow conditions

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* This number differs from that in table 2 by 0.50 in. because of differences in the definition of a precipitation day. The United States definition is used here and the Canadian definition is used in table 2. The heavy rainfall period from 0700 GMT, March 31, to 0700 GMT, April 1, 1972 caused the discrepancy.

Figure 5.--FINAL precipitation totals (in.) for the Field Year (April 1972 through March 1973).

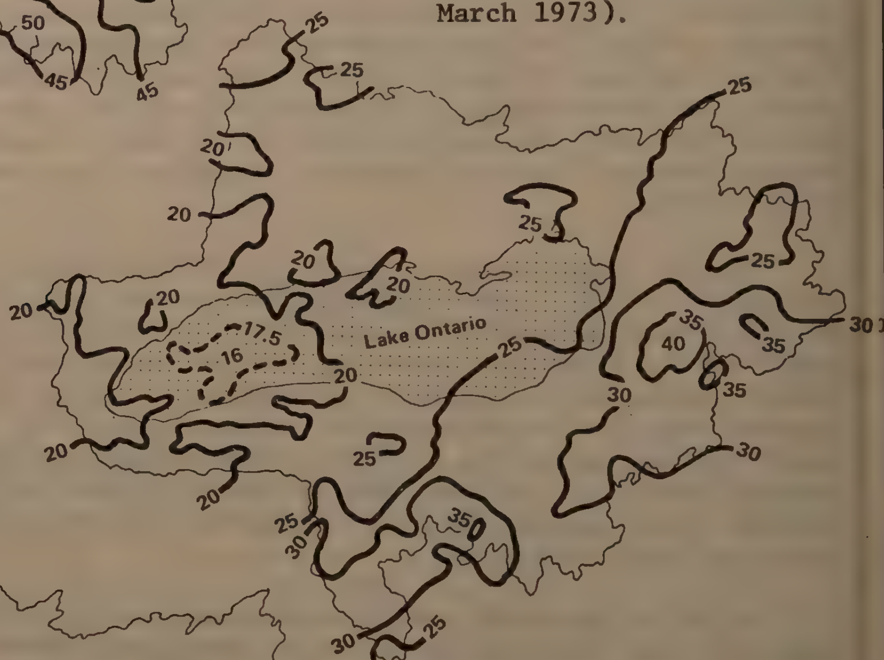

Figure 6.--FINAL precipitation totals (in.) for the period May through October 1972.

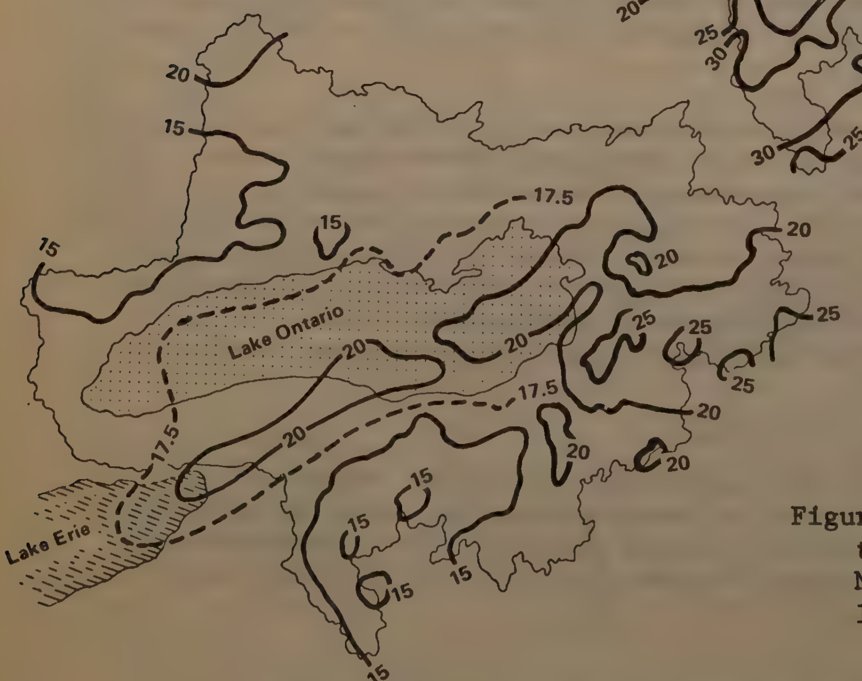

Figure 7.--FINAL precipitation totals (in.) for the period November 1972 through March 1973.

along the southwestern shore of Lake Ontario caused errors in the FINAL totals. Unfortunately, the reliability of the winter precipitation estimates is questionable because of the undercatch of most gages during snow. This problem is discussed further in sections 2.1.3 and 5.1.

Analysis of the FINAL rainfall measurements over the lake and in the immediate vicinity for May through October showed a minimum of rainfall over midlake (more than 15 km from shore). The precipitation tended to increase rapidly from the shoreline to 15 km inland. The immediate shoreline averaged 4.9 percent more rain than the lake. At an inland distance of 15 km the average increase over the lake was 10.5 percent, which was concentrated at the east end of the lake. The average increase from the shoreline to 15 km inland was 5.6 percent; however, the increase was 11.3 percent for the east end of the lake and only 1.0 percent in the Toronto vicinity. The latter increase compares closely with the 1.4 percent average increase obtained from 16 gages in the Toronto area for a 10-year period. Bolsenga, while selecting his gage network for estimating lake precipitation, found that inclusion of gages removed from the immediate vicinity of the lake produced a systematic increase in the overlake estimates for the warm season and a decrease for the cold season. The question arises as to whether the decrease in rain as measured by gages during warm season near the shore is real, or whether it is the result of gage undercatch because of exposure to higher winds. It is believed the minimum is real for two reasons. First the "shoreline gages" were generally not located directly on the shore and the exposures similar to inland gages, and, second, the radar showed the average rainfall to increase away from the shoreline. Thus, when land gages are used in estimating overlake precipitation, it is important that they be located close to the shore and well protected from wind.

4.3 Significant Precipitation Events

During IFYGL, the major precipitation event was the result of Agnes, a hurricane which moved over the Gulf Coast of Florida and then tracked north-northeast to near New York City. The storm produced up to 14-in. rainfalls in the southern portion of the watershed but less than 2 in. in some of the northern portions. Many reports on this storm have been written (e.g., Phillips and O'Donnell, 1975; Miller and Riedel, 1973; Wilson and Pollock, 1974).

The other precipitation events during the year were not exceptional enough to attract much attention. Table 6 lists 24 of the larger ones, which resulted in approximately half the total precipitation during the year. Wilson (1975a) has presented isohyetal analyses of several of these events, and the August 14-15 storm has been studied by Hogg and Pollock (1975).

4.4 Effects of Lake on Precipitation

In section 4.2 it was observed that during the warm season the lake received less rain than the surrounding land, and that during the cold season a precipitation maximum occurred over the lake and extended downwind. It is hypothesized that the relatively cool air over the lake during the warm

Table 6.--Major IFYGL precipitation events

Period of events*			Watershed average precipitation (in.)	Length (days)	Type of storm
1972	April	12-14	0.58	2	Frontal low (988 mb)
	May	1-3	0.85	2	Frontal thunderstorms
	"	15-17	0.73	2	Weak low, thunderstorms
	"	30-June 2	1.48	3	Frontal coastal low (1003 mb) ++
	June	15-16	0.70	1	Frontal thunderstorms
	"	20-24	3.55+	4	Hurricane Agnes
	"	29-30	0.56	1	Trowal
	July	13-16	1.05	3	Frontal thunderstorms
	Aug.	2-3	0.53	1	Frontal low (1003 mb)
	"	6-8	0.95+	2	Frontal low (988mb)
	"	14-15	0.24+	1	Frontal thunderstorms
	"	23-24	0.21+	1	Frontal thunderstorms
	Sept.	29-30	0.96	1	Frontal low (987 mb)
	Oct.	6-7	0.97	1	Frontal coastal low (984 mb) ++
	"	22-24	1.11	2	Frontal low (1002 mb)
	Nov.	2-3	0.38	1	Frontal low (988 mb)
	"	7-9	1.51	2	Frontal coastal low (984 mb) ++
	"	25-27	0.81	2	Frontal coastal low (976 mb) ++
	Dec.	12-13	0.85	1	Frontal low (994 mb)
	"	15-16	0.72	1	Frontal coastal low (984 mb) ++
1973	Jan.	22-23	0.53	1	Frontal low (990 mb)
	"	1-3	0.95	2	Frontal low (974 mb)
	"	14-15	0.34	1	Frontal low (988 mb)
	Mar.	16-18	1.38	2	Frontal low (990 mb)
			21.94	40	

* From 7 a.m. on the first day to 7 a.m. on the last day.

\+ Isohyetal analyses for these storms, as well as for the 1-day periods ending at 7 a.m. on August 28, October 19, January 10, and January 31, have been presented by Wilson (1975a).

++ The term "coastal low" is used to describe a low pressure system that moved from Florida northeastward following approximately the coast of the Atlantic Ocean.

season frequently inhibits the growth of convective storms over the lake, and that, conversely, during the winter the relatively warm lake initiates convective instability through the flux of heat and moisture into the cold air advecting over the lake.

One would expect that the major reduction in overlake rainfall during the warm season would occur on days when the convection has its roots near the surface. Generally, these would be the days when the convection is initiated by local conditions rather than being associated with large-scale weather systems. The percentage of the land basin receiving rain during a day was used to differentiate between days with large-scale organized convection and days with localized convection. This procedure was successful in isolating many of the days when the overlake rainfall was less than that over land. On days when the percentage of the land basin receiving rain was less than 70 percent, the rainfall was 402 percent higher than over the lake. On days when over 70 percent of the land area received rain, on the other hand, the amount was only 14 percent more than over the lake. Ninety-three percent of the total rain fell on days when the coverage was over 70 percent, although these days accounted for only half of the days with rain. Thus, the magnitude of the overlake reduction for a particular month or warm season depends on the number of days the rain is associated with large-scale organized convective systems.

Figures 8a and 8b show the total rainfall for May through September, when the rainfall coverage was less than 70 percent and greater than 70 percent, respectively. The minimum over the lake for days with less than 70 percent coverage is quite apparent in figure 8a, and the heavier rainfall amounts appear to be randomly distributed at distances far from the lake. For the days with greater than 70 percent coverage, shown in figure 8b, the heavy rainfall associated with Hurricane Agnes is not included, since it tends to dominate the rainfall patterns. The most significant feature here is the rainfall maximum in the hilly region east of Lake Ontario, which is apparently orographically induced. There is no obvious lake effect for these days.

During the cold season, localized rain or snow bands occur when cold air passes over the relatively warm lake waters. Usually referred to as "lake effect" storms, they are generally associated with a long overlake fetch of wind combined with an unstable temperature lapse rate. Holroyd (1971) has shown that nearly all "lake effect" storms occur when the 850-mb temperature is more than 13°C colder than the lake surface temperature. (The dry adiabatic temperature decrease is approximately 13°C between the surface and 850 mb.) Thus, it is expected that the lake would have the strongest effect on the precipitation distribution on days when the 850-mb temperature is more than 13°C colder than the lake, and the weakest on days when the 850-mb temperature is less than 7°C colder than the lake. (The saturated-adiabatic temperature difference between the surface and 850-mb is approximately 7°C.)

Days were grouped depending on the temperature difference between 850 mb and the lake (lake minus 850 mb), as follows: unstable (> 13°C).

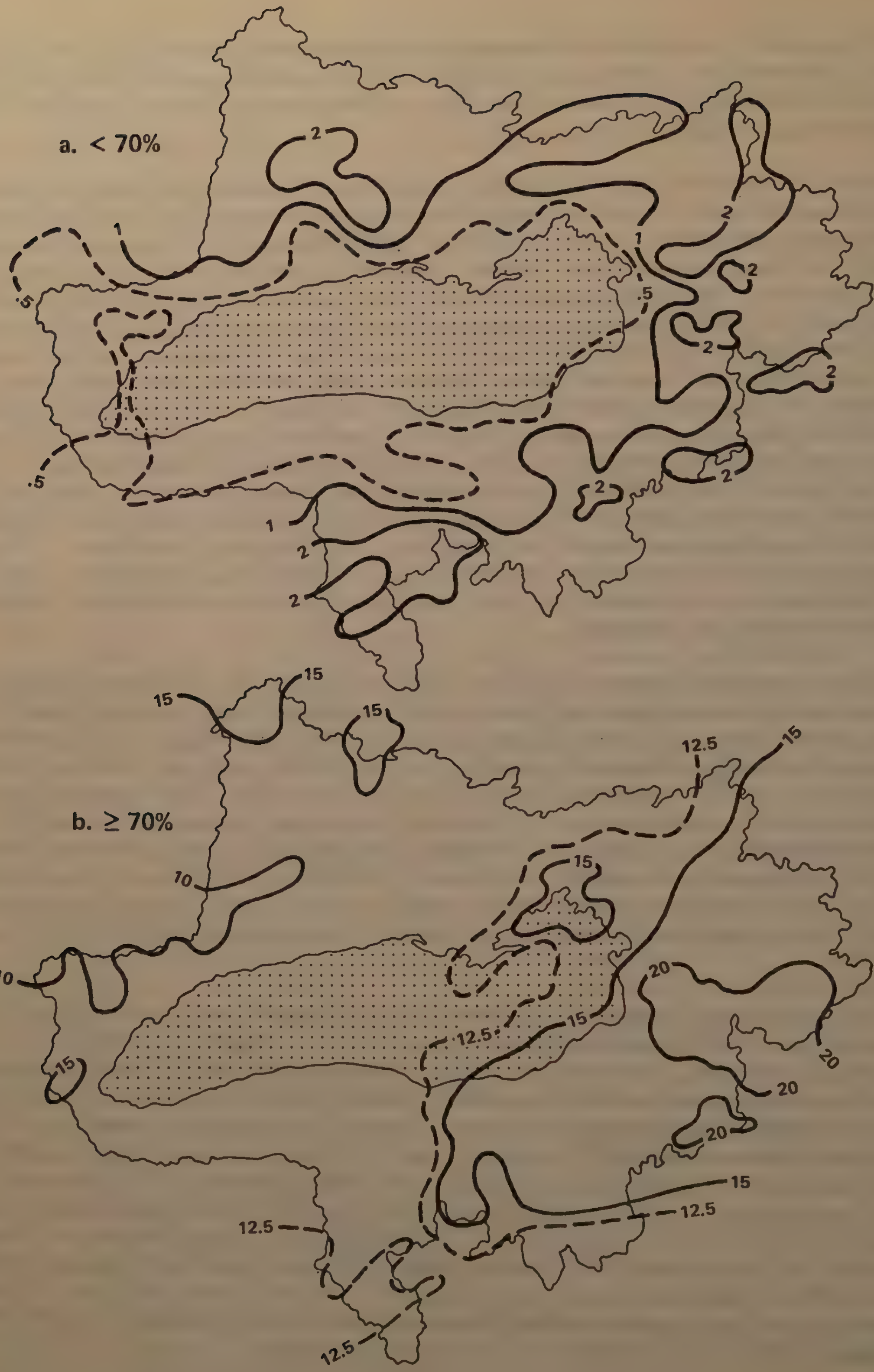

Figure 8.--Rainfall totals (in.) May through September for days with the indicated percentage of the land basin receiving rain. Days without radar data are not included, nor is Hurricane Agnes.

conditionally stable (7° - 13°C), and stable (< 7°C). Figures 9a, 9b, and 9c show the precipitation distribution for each of these stability criteria. The first two give evidence of lake-generated precipitation. The precipitation distribution for the unstable days has a maximum axis extending northeast from Lake Erie to Lake Ontario, then eastward through Lake Ontario into the hills east of the lake. Another maximum is seen over the extreme northern portion of the watershed, which is directly east of Georgian Bay and Lake Huron. This precipitation distribution is much as one would expect from "lake effect" storms. The precipitation distribution for the days of conditional stability differs from the unstable days in that the maximum northeast of Lake Erie is significantly less and the maximum associated with Georgian Bay is absent. The stable days account for 77 percent of the total precipitation and for 47 percent of the precipitation days. The maximum extending from the lake toward the northeast during the stable days is apparently not caused by either the lake or the topography. However, the usual orographic maximum east of the lake is present.

The distribution of precipitation over the Lake Ontario basin is strongly affected by the lake and by hills. The largest precipitation amounts occur over the Tug Hill plateau east of Lake Ontario. These hills are only 300 to 450 m above mean sea level (MSL); others, along the southern and eastern watershed boundary, reach 600 to 750 m MSL. The precipitation maximum over the Tug Hill plateau can be attributed to the fact that the plateau is the first obstacle to the prevailing westerly air flow after a long fetch over low flat terrain, much of which is covered by water.

In summary, the relatively cold lake waters frequently suppress shower activity over the lake during the warm season, particularly when the precipitation is not initiated by large-scale well-organized weather systems. During the cold season, the lake frequently stimulates precipitation over and downwind of the lake through the flux of heat and moisture to the relatively cold air. Additional details concerning the effect of the lake on precipitation are given by Wilson (1977).

5. ACCURACY OF PRECIPITATION MEASUREMENTS

5.1 Gage Errors

Two types of errors are inherent in areal precipitation estimates based on gage observations. The first, systematic, type, stems from the inability of a gage to measure accurately the precipitation falling at a point, mainly because the gage disturbs the airflow. This error usually results in an underestimate, and the error is much larger for snowfall than for rainfall. The second, random, type of error arises because gage measurements made at a point are used to estimate the precipitation over an area where large precipitation variations may exist. This spatial variability is normally largest for convective type rainstorms.

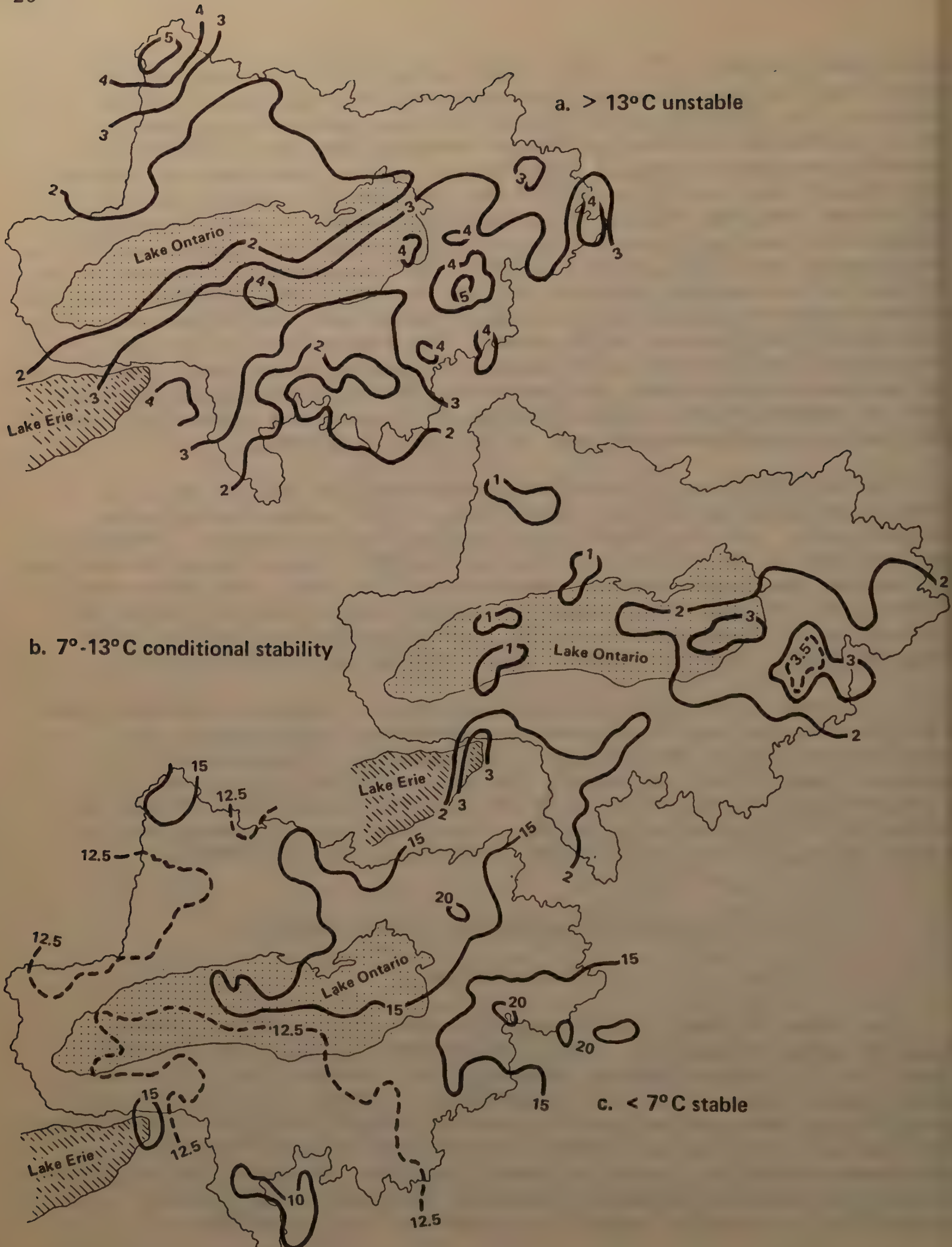

Figure 9.--Precipitation totals November through March for days when the 850-mb temperature is a. > 13°C, b. 7-13°C, and c. < 7°C colder than the lak

5.1.1 Systematic Errors - Rainfall

Many small errors, such as evaporation from the gage, adhesion of the rain to the gage, and the like, result in approximately a 1.5 percent underestimate of the "true" rainfall. Errors caused by the flow of air around the gage result in a 5 to 80 percent underestimate (Rodda, 1971). The magnitude of this underestimate depends on the exposure of the gage, the height of the gage's orifice above ground, and the shape of the gage. A gage installed with its orifice at ground level and surrounded with an antisplash grid eliminates the latter error. Both the United States and the Canadian standard rain gages have been compared with such a pit gage. The former was found to catch about 6 percent less rain (WMO/UNESCO, 1974); the latter, about 4.8 percent less. The United States comparisons were based on only 2 years of observations from three stations, and the Canadian on 4 partial years from three stations. Sanderson (1975) compared 6 years of simultaneous measurements at Windsor and found that the Canadian standard gage caught 1.2 percent more rain than the United States standard gage, which is consistent with the other comparisons. Harris and Carder (1974), however, compared 10 years of simultaneous measurements in Alberta and found that the Canadian standard gage caught 2.2 percent less rain than the United States standard gage.

Canadian recording rain gages are normally operated beside a standard gage and adjusted to agree with the total rainfall measured by the standard gage. The areal average rainfall estimates (except the FINAL) presented in this report are therefore based almost entirely on standard gage measurements, or the equivalent, and should be underestimates of the "true" overland rainfall values by approximately 7 percent.

5.1.2 Systematic Errors - Snowfall

Very large errors are possible when measuring snowfall. For example, Ferguson and Pollock (1971) found that Fischer and Porter precipitation gages with Alter wind shields in exposed locations in the prairies measured only one-third as much snowfall as a snow ruler (using a density of 0.1) or only one-half as much as a Nipher snow gage. The best method for making a good snowfall measurement is to locate a gage in a very sheltered location.

During IFYGL, almost all Canadian measurements of the depth of freshly fallen snow were made with a snow ruler and assuming a density of 0.1. Ferguson and Pollock (1971) found that the average ratio between Nipher and snow ruler measurements in southern Ontario was 0.082, based on 71 station months of simultaneous measurements. The use of an assumed density of 0.1 would thus result in the Nipher measurements averaging 18 percent less than the snow ruler measurements.

Goodison (1975) found that the Nipher gage caught very close to the "true" snowfall and at certain wind speeds even overcaught. The average for a winter showed the Nipher catching 93 to 110 percent of the "true" snowfall as measured by a sheltered snow board. The ruler measurements adjusted by an assumed density of 0.1 should therefore give approximately a 15 percent

overestimate on the average of the correct water content of the snowfall. In individual storms there could be a very large discrepancy because of snow crystal shape, size, and wetness. Freshly fallen snow produced by snow flurries in the lee of the Great Lakes has been reliably measured as having a density as low as 0.02. Densities of freshly fallen snow as large as 0.2 have also been measured. This variation in density from storm to storm leaves a range of uncertainty by a factor of 10 in the Canadian IFYGL measurements for a particular storm. In addition, snowfall measured by snow rulers and with an assumed density of 0.1 will result in large overestimates of the true water content in areas with large lake effect snowfalls.

Snowfall measurements by the United States during IFYGL were usually made with the United States standard rain and snow gages, a few of which have Alter shields to reduce the effect of wind on gage catch. Sometimes measurements were made with a snow ruler or snow board. Hamon (1972) and Larson and Peck (1974) have estimated the accuracy of shielded and unshielded gage measurements of snowfall. They have shown that for a wind speed of 10 mi/h (16 km/h) the unshielded gage catch is about 45 percent deficient and for a 20 mi/h (32 km/h) wind about 70 percent deficient. A shield can reduce this error by about one-third to one-half.

Because of the various methods used by the United States in measuring snowfall during IFYGL and the nonuniform exposure of the gages, no definite estimate of the difference between the ANL2 estimates and the true snowfall is possible. However, comparison of the Oswego snow network gage observations with the ANL2 estimates indicates that the ANL2 technique underestimated the winter precipitation over the Oswego network by 14.7 percent (table 7). Considering that 50 percent of the winter precipitation was snow, that the gage undercatch for snowfall is much larger than for rainfall, and that ANL2 was based entirely on measurements by the standard climatological network, it is believed that the standard climatological network underestimated the snowfall near Oswego by approximately 25 to 30 percent. Sanderson (1975) found at Windsor that the United States standard gage with an Alter shield underestimated the Canadian snow ruler measurements by 12.5 percent (assuming a density of 0.1). Harris and Carder (1974) found in Alberta that the United States standard gage underestimated the Canadian Nipher gage by 20 percent. The above findings suggest an underestimate of the average snowfall over the United States land basin by 10 to 30 percent based on the gage measurements alone, without any radar measurements.

5.1.3 Random Errors

Random errors occur because a precipitation gage network samples the precipitation occurring over an area at only a few points, and substantial spacial variations in precipitation are possible. Also, the longer the time period over which the precipitation is being estimated, the more closely the gage observations can be expected to yield a true estimate of the areal average precipitation, assuming that there is no bias in the gage measurements.

One method of estimating the difference between the true areal average precipitation and the estimate obtained from precipitation gages is (1) to use a very dense network of precipitation gages and to assume that the average of these observations is effectively the true areal average precipitation, and (2) to use a subset of the observations to estimate the areal average. The differences between the two sets of values can then be considered an estimate of the error resulting from sampling the precipitation at only a few points. Huff (1970) used this method in Illinois with networks of 49 rain gages in an area of 1000 km^2 and the same number of gages in an area of 1400 km^2. From these data, he derived equations expressing the error as a function of area, gage density, amount of precipitation, and length of time.

Using Huff's equations, errors in the monthly estimates by the various IFYGL investigators were found to be 0.8 to 1.8 percent except in the case of Phillips' estimate, where the error was about 3.5 percent. As shown in table 5, the differences between the various estimates and the FINAL estimates are 5.7 to 6.0 percent for Phillips, 1.2 to 6.2 percent for the other estimates for the entire land basins, and 6.7 to 10.4 percent for the lake. These differences are about twice the magnitude predicted by Huff, except for the lake where they are about 5 times those predicted by Huff.

5.2 Radar Errors

During the past 20 years, numerous studies have been made of weather radar measurements of precipitation, and have shown a wide range in reported accuracies. Measurements have been made for a large variety of radars for different radar ranges, area sizes, time intervals, geographical locations, weather types, and data processing techniques, all of which are factors that can influence the accuracy of radar measurements. Thus, the wide range in reported accuracies is not difficult to understand. Among factors known to contribute to errors in radar precipitation measurements are the following:

- Anomalous propagation.
- Beam blocking.
- Errors in radar calibration.
- Time changes in radar sensitivity.
- Reflectivity losses due to precipitation attenuation.
- Attenuation during periods of heavy rain on the radome.
- Received power averaging errors in regions of very strong precipitation gradients.
- Nonuniform filling of the radar beam by precipitation.
- Beam interception of the freezing level.
- Presence of hail.
- Variation in the drop-size distribution.
- Variation in snow-crystal type.
- Strong localized air divergence.
- Strong vertical air motions affecting drop or flake fall speed.
- Evaporation or growth of precipitation below the radar beam.
- Wind drift of precipitation below the beam.
- Frequency of radar collections.

Because many of these error factors vary considerably in space and time, the accuracy of the precipitation estimates increases as the area and time interval increase. Also, many become more important as the radar ranges increases, and higher accuracies are therefore generally obtained at closer radar ranges. Because of these many uncertainties, it became apparent that some means was required to maintain quality control of the radar-derived precipitation estimates for IFYGL. Rather than to attempt quantitative correction of these uncertainties, which are continually varying in space and time, it was thought more practical to use precipitation gages to correct or calibrate the radar estimates. The philosophy behind such a procedure of combining radar and gage data is to use the radar to specify the spatial precipitation distribution and the gages to specify the precipitation magnitude.

Experimental results from Oklahoma, Florida, the Great Lakes, and England, show that the average errors in gage-adjusted radar precipitation estimates are generally between 10 and 20 percent (Wilson, 1976a). These results are for measurements under the following approximate conditions: area, $\geq 170\ km^2$; time interval, ≥ 3 hr; radar range, 45 to 110 km; and calibration gage densities, $\geq 1/3400\ km^2$. Errors less than 10 percent are likely only for radar ranges closer than 46 km.

The gage-adjusted radar estimates are superior to those derived from either radar or gage data alone. However, the improvement is very dependent on the length of the measurement period, the size of the area, and precipitation variability. The improvement is greatest for showery precipitation over small areas for short time periods. For average daily totals over an area the size of the Lake Ontario basin, the radar data provide little improvement over estimates from gages alone, simply because the gage density (average, 350 to 700 km^2/gage) is sufficient to adequately sample the rainfall for such a large area. The sampling error is, in fact, similar to the error inherent in individual gage measurements.

5.3 Mesonetworks, Lake, and Watershed

The accuracy of the precipitation estimates for the lake and watershed during IFYGL can be estimated only indirectly by extrapolating the results for the gage mesonetworks. Opposing factors that act to produce different errors than those observed for the first-order and climatological stations include a decrease in error as the area for computing the mean precipitation increases and an increase in error for areas with fewer calibrating gages.

Data from the Bowmanville, Rochester, and Oswego mesonetworks were not used in deriving either the ANL2 or the FINAL precipitation estimates. Thus the mesonetwork data can be used an an independent test of the accuracy of the estimates. The average absolute errors in the ANL2 and FINAL daily, monthly, and seasonal estimates for the Oswego and Rochester networks are given in table 7. In presenting these figures it is assumed that the average of the network gages is the true average for the network.

Table 7.--Average absolute error of the ANL2 and FINAL precipitation measurements for the mesonetworks

Gage mesonetwork	Radar range (km)	Average error (percent)					
		Daily		Monthly		Seasonal	
		ANL2	FINAL	ANL2	FINAL	ANL2	FINAL
Oswego	42	20.7	18.7	14.6	5.0	14.7	0.1
Rochester	92	21.7	22.5	5.9	8.5	2.3	1.6

The results for the Bowmanville network are not shown in table 7, because the three climatological gages within and on the immediate edge of the network systematically measured more rainfall than the network gages. This difference is probably artifical, resulting from errors in calibrating the network gages. Since these three gages heavily influence both the ANL2 and FINAL estimates, meaningful comparisons are not possible.

The relatively large errors in the ANL2 estimates for the Oswego network are attributed to the undercatch of the climatological gages during snow and to the existence of a precipitation maximum over the network that is not adequately sampled by the climatological gages. The error in the FINAL estimates decreases from an average of 19 percent for the daily values to 5 percent for the monthly. The FINAL estimates for the Oswego network are more accurate than those for the Rochester network, most likely because of the closer radar range of the Oswego network.

The ANL2 and FINAL estimates are very similar in the case of the Rochester network. The average error decreases from approximately 22 percent for the daily estimates to 7 percent for the monthly and 2 percent for the yearly. This similarity in the ANL2 and FINAL estimates was expected because of the high density of climatological gages near the Rochester network (170 km^2/gage).

Wilson (1975a) has combined the above results with other analyses to estimate the errors in the FINAL precipitation estimates. These errors are given in Table 8.

Estimates of the average daily rainfall over the watershed and lake differed only slightly from those obtained based solely on gage data. Thus, it is concluded that the radar observations contributed little to improving the estimated average rainfall totals for the lake and watershed. This is true only, however, for the average rainfall over areas of many thousand

square kilometers or for smaller areas with a high density of gages. While radar provides extensive detailed coverage for areas between gages, it does not improve the areal rainfall estimates since the gages already adequately sample the area rainfall, and the gage density over the watershed (averages of 350 to 700 km^2/gage) was in fact, sufficient to measure the areal rainfall within the error limits of the individual gage measurements. Also, the close agreement between the ANL2 and the FINAL estimates for the lake indicate that the nearshore gages closely measured the average rainfall over the lake. It is surprising the gages do so well since it was found, with a high degree of confidence, that the shoreline areas measured from 5 to 10 percent more rain than the lake.

The above discussion is only applicable to the warm season. The accuracy of the estimates for the cold season is particularly difficult to assess because of the uncertainties in gage or ground measurements of snowfall. The only reliable ground-truth measurements were made within the Oswego network. Based on these data and a literature survey, it is estimated that the United States climatological gage measurements average 8 to 18 percent too low during the cold season because the snowfall measurements average 10 to 30 percent too low. The Canadian climatological gages may average as much as 4 percent too high during the cold season because they overestimate the snowfall by up to 15 percent. In addition, it was demonstrated that the climatological gages are not very successful in estimating overlake precipitation during "lake effect" storms. The radar apparently contributes more to increasing the accuracy of the overlake

Table 8.--Estimated average error in the FINAL lake and watershed precipitation measurements

Area	Average error (%)	
	Daily	Monthly
Watershed	< 10*	< 5*
Lake	20-30+	10-15+

* In addition, measurements average 7 percent too low for the warm season and 6 to 16 percent too low for the cold season in the United States watershed, and perhaps as much as 4 percent too high for the cold season in Canada.

\+ In addition, measurements average 7 percent too low for the warm season, but are only slightly too low during the cold season.

estimates during the cold season than during the warm season. However, considerable care must be taken to ensure that only gages well protected from the wind are used for adjusting the radar estimates.

6. PROBLEMS AND RECOMMENDATIONS

As expected from a large data collection and analysis effort, such as IFYGL, a number of problems were encountered. As a result, several recommendations can be made to assist similar future programs.

6.1 Gage Measurements

The major precipitation measurement problem is the water content of falling snow. Neither the Canadian nor the United States (National Weather Service) measurements of snowfall are standardized, and they vary greatly in accuracy from storm to storm and location to location. Water contents are determined by various techniques (section 5.1.2), all associated with errors peculiar to each location. The measurement method used by a particular station in the United States climatological network for a particular storm is not always known, which complicates any evaluation of measurement errors. The snowfall data from the Oswego network demonstrated that high-quality snowfall measurements are possible if care is taken to locate observation sites in areas well protected from wind. Thus, it is recommended that snowfall water content measurements from the climatological networks be used with great caution and that, if good snowfall measurements are required, special care be taken to select or establish sites well protected from wind.

Two other problems were associated with the standard United States and Canadian climatological network gages; errors in recording the precipitation measurements, and lack of time resolution in the data. The most common errors in recording the precipitation was to enter the precipitation on the wrong day, record zero precipitation for days on which it obviously occurred, and to read the gage at an unscheduled time. The radar data were particularly helpful in isolating these errors. For these reasons, it is recommended that climatological network data be carefully checked for obvious errors before use. Less than 20 percent of the climatological gages are recording gages; the others are generally read and reported once a day, and then at different times. Most gages are read between 7:00 and 9:00 a.m., which means that when significant precipitation occurs during this period considerable error exists in the area average 24-hr totals.

The Fischer and Porter recording gages provide only a 0.1-in. resolution. Except for heavy precipitation, this resolution is too coarse for gage adjustment of radar estimates.

6.2 Radar Measurements

During the first 2 months of the Field Year, less than 30 percent of the radar data were successfully collected. A 3-month "shakedown" period

was originally planned before the start of the Field Year. However, circumstances limited this period to 1 day for the Buffalo radar and 1 month for the Oswego radar. The poor success in data collection during the first 2 months emphasizes the importance of an adequate "shakedown" period.

With the exception of a 27-day period, when hardware problems plagued the tape recorder, the data from the Oswego radar were more than 99 percent complete. Unfortunately, this was not true of the Buffalo radar, for which there were frequent data gaps of several hours during a storm. These data gaps often resulted from the operator forgetting to return the system to the automatic collection mode after an interruption for operational reasons. The obvious recommendation for the future is to adjust the manual override feature to be effective for only one collection at a time.

There was serious blocking of the Oswego radar beam for three sectors. Much of the blocking, which was caused by trees near the radar, could have been eliminated by raising the antenna 10 to 20 ft. When choosing a radar site and planning the data collection, the problem always arises as to how high to mount the radar and what beam elevation angle to use. Generally, the radar should be mounted only high enough to clear nearby obstacles so as not to unnecessarily increase the ground clutter pattern. When the radar antenna is at low elevation angles, the ground can cause unpredictable changes in the beam radiation pattern. Thus, it is desirable to elevate the radar antenna to an angle approximately equal to the radar beam width (Smith, 1972). The result, however, is a greatly reduced range for detecting precipitation and for obtaining reliable precipitation measurements, particularly during the winter. Experience gained from the IFYGL program suggests that, unless data are desired only for very close ranges, the overriding consideration should be to keep the beam as low to the ground as possible. Generally, an antenna elevation angle of 0.5° should prove the best compromise.

The quality of the radar precipitation measurements varied considerably with range. The range of useful measurements was dependent on the freezing level height, and the vertical extent of the precipitation. It was essential, therefore, to make range adjustments in the radar estimates before adjustment based on gage data.

7. CONCLUSIONS

Precipitation estimates for Lake Ontario and/or its watershed for the Field Year were made by eight techniques by seven investigators. The estimates were based on precipitation gage data, with the exception of one technique, FINAL, in which both weather radar and precipitation gage data were used. Considerable effort was devoted to developing a very successful procedure by which data from two radars and 167 precipitation gages were combined to produce detailed FINAL daily precipitation analyses for the entire Lake Ontario basin. The technique combines two objective analyses of the precipitation field: one based on precipitation gages, and other on radar after calibration by the precipitation gages. The FINAL analyses are

molded to fit the gage observations closely, while maintaining the variability between gages observed by radar. This was the first large-scale effort to obtain precipitation estimates from combined radar and gage data for an entire year for a wide variety of weather situations. The success of the program illustrates the utility of the procedures. It became apparent that great care is required in selecting both the radar and gage sites. The gages should have similar exposures, and all should be well protected from wind. The radars should be located to minimize ground clutter and beam blocking.

Comparisons between the techniques in terms of average yearly, monthly, and daily precipitation for the lake and/or watershed showed a very high correlation. The FINAL yearly totals averaged between 0 and 6 percent more than the others. The average monthly differences between the FINAL and the other techniques were between 1 and 10 percent, and daily differences averaged between 8 and 38 percent. Daily estimates were derived by only two other techniques.

Data from three precipitation gage mesonetworks were available for assessing the accuracy of, but not to obtain, the FINAL estimates. Based partly on these comparisons, the average random error in the overland and overlake monthly measurements was estimated at less than 5 percent and between 10 and 15 percent, respectively. In addition, it is estimated the measurements averaged 7 percent too low, except overland during the cold season when the snowfall was estimated to be 5 to 25 percent too low in the United States but perhaps as much as 15 percent too high in Canada. As a result, the total precipitation estimate during the cold season was estimated as being 6 to 16 percent too low in the United States but perhaps 4 percent too high in Canada. Precipitation measurement and accuracy figures are much more uncertain for the cold than for the warm season, primarily because of the great uncertainty in gage snowfall catch

Although the combined radar-gage technique provides extensive detail in the precipitation field, the resulting average precipitation estimates for the lake and watershed are not much better than those derived from gage data only, because the gage density is sufficient for estimating accurately the average watershed precipitation. The rainfall over the lake during the warm season was apparently accurately estimated by the nearshore gages. These estimates were suspect initially, because the radar analysis indicated that the shoreline averaged 5 percent more rain than the lake, and 15 km inland the increase was 10 percent. However, most of this increase was concentrated over the eastern end of the lake, probably the result of an orographic effect produced by the Tug Hill Plateau. By force of circumstance, the rain estimates over the eastern portion of the lake were based primarily on an island gage instead of a land gage, and hence the gage-only techniques provided better estimates than otherwise expected.

There were many days when the lake had a significant effect on the precipitation, days on which convection was initiated more by local conditions rather than by large-scale dynamic weather processes. During the warm season, it was observed that for scattered shower situations (less than

70 percent of the land area receiving rain for the day), the land received more than five times the rain that fell over the lake. These days account for half the precipitation days, but they contribute only 7 percent of the total rainfall for the season. In contrast, for the remaining days, the land received only 14 percent more rain than the lake.

During the cold season the lake frequently stimulated precipitation over and downwind of the lake when the temperature difference between the lake and 850 mb produced an unstable or conditionally unstable temperature lapse rate. About half the precipitation days fell in these categories, but they accounted for only 23 percent of the total seasonal precipitation.

Thus, during the year about half of all the precipitation days are significantly affected by the lake, suppressing overlake precipitation during the warm season and initiating precipitation activity during the cold season. These are, however, days when the precipitation is relatively light and scattered. Thus, the overall effect of the lake on season or yearly precipitation totals is not as impressive as one might expect from observation of the day-to-day precipitation patterns.

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APPENDIX

Specification of Precipitation Gage Observation Systems

Background information on the United States observation system is given is "U.S. IFYGL Precipitation Data Acquisition System," IFYGL Technical Manual Series No. 4 (Hansen et al., 1973), and will not be repeated here. This appendix serves primarily to provide details on the equipment used for the Canadian precipitation measurements.

A.1 Canadian Climatological Networks

Standard Instruments

The main instrument for measuring rain is a copper cylinder with the orifice at a height of 30 cm above ground and having an area of 65.5 cm^2. The main instrument for measuring snowfall is a ruler, which is used to measure the depth of freshly fallen snow to the nearest 0.1 in. The depth is converted to water content by assuming a density of 0.1. During IFYGL, approximately 180 stations operated with these instruments in Canada at various times as part of the standard Canadian climatological network within or very near the watershed.

Measurements with these standard instruments are normally taken about 7 to 9 a.m., and the recorded amounts are considered to have fallen on the previous calendar day. A second observation is often taken later in the day.

Starting in 1972 the copper rain gages were being replaced by plastic gages with an orifice area of 100 cm^2 and with the orifice 40.6 cm above the ground. Very few of the plastic gages were in use during IFYGL.

Other gages most frequently used within the Canadian climatological network are described below.

Nipher Snow Gage

This gage consists of a cylinder with an orifice 12.7 cm in diameter mounted inside a spun aluminum Nipher type shield. The top of the shield and the orifice can be moved vertically to position them 1.52 m above the snowpack surface. The snow caught in the cylinder is melted and its volume measured. Generally, this gage is used only at airports and Canada Department of Agriculture stations (approximately 10 in the Lake Ontario watershed). At the airports, the gages are normally read every 6 hr.

Tipping Bucket Rain Gage

This rain gage has an orifice 25.4 cm in diameter and 75 cm above ground level. The rain flows into a bucket mounted on a balance arm. The balance is adjusted so that when 0.01 in. of rain falls into one bucket, the arm moves, emptying one bucket and moving the second bucket into

position to catch the rainfall. Because of the finite time required for the second bucket to be moved into position once the first bucket has been filled, this gage tends to undercatch during intense rainfalls. The standard practice in the climatological network is to adjust the tipping bucket observations to agree in total amount with the daily reading from a collocated standard rain gage. The tipping bucket gage is normally operated with a chart recorder that has about a 5-min time resolution, but only 1-hr amounts are abstracted normally. Approximately 50 of these instruments were operated in the watershed over various time periods during the Field Year as part of the standard Canadian climatological network.

Fischer and Porter Precipitation Gage

The Fischer and Porter precipitation gage collects, measures, and records the weight of all forms of precipitation (e.g., rain, freezing rain, snow). The gage is completely automatic and can be left unattended for up to 3 months.

When installed, the base of the gage is approximately 1.2 m above ground and the orifice approximately 2.3 m above ground. The orifice is 20.3 cm in diameter; the body of the gage below the orifice expands gradually to 50 cm in diameter.

The gage can record a maximum of 19.9 in.of liquid precipitation. It converts the weight of the accumulated precipitation into inches of depth of water and records the depth to the nearest 0.1 in. on paper tape. A solid-state timer controls the time interval at which the depth of precipitation is recorded. In Canada, a time interval of 15 min was used. In the United States, a time interval of 1 hr was used for the gages located on the islands in Lake Ontario and an interval of 15 min for the gages in the Rochester network. During the winter, the frozen precipitation was melted with antifreeze. During the summer, a thin layer of oil was used to retard evaporation. All the gages were equipped with Alter wind shields, except the gages in the Rochester network.

A.2 Bedford Towers

Three Bedford Towers were installed during IFYGL. These towers floated vertically, carrying dual receiver rain gages at the top, approximately 18 m above the water surface. Many other meteorological variables, including wind, were measured. Their locations and periods of operation were as follows:

Location	Lat. N	Long. W	Began	Ended
Oswego	$43^{\circ}35'$	$76^{\circ}22'$	Aug. 11, 1972	Nov. 16, 1972
Cobourg	$43^{\circ}50'$	$78^{\circ}3'$	June 2, "	Nov. 21, "
Port Credit	$43^{\circ}27'$	$79^{\circ}31'$	May 16, "	Nov. 21 "

The tower rain gage consisted of a funnel 25.4 cm in diameter open upward with a finned opening under the funnel (fig. A.1). This second opening presented the same area in the horizontal as the funnel did vertically, and the same cross-sectional area to each azimuth. The rain caught by each receiver was measured with a resolution of 0.01 in. every 10 min.

Figure A.1.--Dual receiver rain gage.

Testing of the gage is described in a communication from D. Champ of the Atmospheric Instruments Branch, Atmospheric Environment Service (AES): "The following tests were carried out for the dual receiver, during late 1971, and again during the period May to October 1972. The dual receiver was mounted atop a standard AES anemometer mast (10 m) located near the standard pit gage installed at the Woodbridge farm (approx. 45 m distant). Early results in 1971 indicated a possible empirical result which was later shown to be false (poor statistics); the results obtained from all data, Oct. 1971, Nov. 1971, May 1972 and June 1972, analyzed storm-by-storm, led to a result which stood up for all subsequent data and has been used since.

"If P_g = pit gage catch

P_v = vertical catch of dual funnel

P_h = horizontal catch dual funnel

E_1 and E_2 are the residuals (errors)

"Then the following empirical formulas were obtained for storm-by-storm

rainfalls:

$$P_v + 0.05\ P_h = P_g \pm E_1 \quad (1)$$ where the standard deviation of E_1 was 0.02 in.

or

$$\frac{(259)}{(250)} P_v = P_g \pm E_2 \quad (2)$$ where the standard deviation of E_2 was 0.02 in.

"These results held for all cases with winds varying from calm to 52 km/hr gusting to 83 km/hr. For all cases where E_1 or E_2 were greater than their respective standard deviations, the precipitation was showery in nature so that natural variability of precipitation could account for the variation. Equation (2) indicates that redesign of the standard funnel may be possible with good results and yet not be too complicated."

Data from the towers were not used for this report because the data are still being processed.

A.3 Canadian Shoreline Network

Six automatic observing stations were operated near the shores of Lake Ontario. The operation of the precipitation gages at these stations is summarized below. All continued operating beyond April 1, 1973. The reliability percentage is the percentage of the total number of hours for which all six observations per hour were available from the start of observations to March 21, 1973.

Location	Lat. N	Long. W	Began	Reliability (%)
Point Petre	43°50'	77°9'	July 28, 1972	90
Cobourg	43°57'	78°10'	July 28, "	89
Darlington	43°52'	78°47'	July 18, "	87
Toronto Headland	43°38'	79°19'	April 1, "	91
Burlington	43°18'	79°48'	July 4, "	92
Port Weller	43°17'	79°13'	July 6, "	88

The precipitation gage was a volumetric type with an orifice 25.4 cm in diameter located 75 cm above ground level. The volume of liquid precipitation was measured with a 0.01-in. resolution by sensing when a chamber was full and activating a plunger to drain the chamber. Every 10 min the accumulated precipitation was recorded on punched paper tape along with other meteorological variables. During the winter months, a thermostatically controlled heater was used to melt frozen precipitation.

Data from this network were not used for this report because processing of the data had not been completed at the time of writing.

A.4 Island Chain

A network of Fischer and Porter precipitation gages (sec. A.1) was operated on islands and along the shoreline of northeastern Lake Ontario. The locations of the gages, times of operation, and reliability are summarized below. The dates represent the first and last complete months with good data. Reliability is given as percent of the total number of months for which monthly total precipitation values are available. The first is the reliability from April 1972 to March 1973; the second is for the period between beginning and ending of operation.

Location	Lat. N	Long. W	Began	Ended	Reliability (%)	
United States						
Galloo Island	43°53'	76°27'	Sept. 1969	Apr. 1974	50	50
Tibbetts Point	44°6'	76°22'	Sept. "	July "	58	78
Point Peninsula	43°58'	76°17'	Aug. "	July "	50	83
Stony Point	43°50'	76°18'	Aug. "	July "	50	72
Southwick Beach	43°44'	76°13'	Sept. "	July "	50	81
Selkirk Shores	43°58'	76°12'	Sept. "	July "	58	75
Canada						
Main Duck Island	43°55'	76°36'	Sept. "	Nov. "	100	78
Pidgeon Island	43°58'	76°49'	Sept. "	Jan. "	17	66
Swetman Island	44°4'	76°33'	Sept. "	Nov. "	67	57

Because of the low reliability of these gages and the substantial under-catch of snowfall, these data were not widely used for this report.

A.5 Bowmanville Network

A network of 12 tipping bucket type rain gages (0.01-in. resolution in depth) were operated with weekly charts that gave a time resolution of 1 hr. The gages were calibrated before installation in the field in April 1972. The gage readings were not adjusted to agree with collocated standard gages, as was the practice with gages in the standard climatological network. The

gages operated with about a 99 percent reliability until their removal on November 16, 1972. Their locations are given below.

Gage No.	Lat. N	Long. W	Gage No.	Lat. N	Long. W
1	44°02'	78°40'	7	43°58'	78°41'
2	44°01'	78°37'	8	43°58'	78°38'
3	44°01'	78°40'	9	43°57'	78°39'
4	44°00'	78°38'	10	43°56'	78°36'
5	44°00'	78°42'	11	43°55'	78°40'
6	43°59'	78°36'	12	43°54'	78°38'

Near gage 12 of this network, a standard rain gage was operated as part of the standard climatological network. In addition, a distrometer (Joss and Waldvogel, 1967) with a volumetric rain gage (sec. A.1) was operated, and data from both were punched on paper tape. All the sensors were within a circle 5 m in diameter on an open grass site. The distrometer and volumetric gage were installed May 5, and removed November 16, 1972. The distrometer had a surface on which raindrops impinge, and the vertical momentum of the raindrops was converted to an electric pulse by a transducer. These pulses were then sorted into 20 classes by drop size and counted. The accumulated counts were recorded on punched paper every 30 s.

The volumetric gage and distrometer data were recorded on paper tape for 73 percent of the total time, but only about 58 percent of the total rainfall was recorded. The two main reasons for loss of data were that (1) the recorder ran out of paper tape if more than about 0.85 in. of rain occurred in a week, and (2) the system depended on line power and did not restart automatically after a power failure.

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